MANAGEMENT OF THE RED SEA CUCUMBER IN SOUTHEAST ALASKA: BIOLOGY, HISTORICAL SIGNIFICANCE IN PACIFIC COAST FISHERIES, AND REGIONAL HARVEST RATE DETERMINATIONS

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FOREWORD

This document is a supplement to Regional Information Report 1J90-30 *Interim Management measures for the Red Sea Cucumber Fisheries in Southeast Alaska.* Included are summaries of the known biology, history of commercial exploitation, and a description of the methods used to estimate harvest rates.

SUMMARY OF SEA CUCUMBER BIOLOGY

The following narrative summarizes the published information of the biology and life history of sea cucumbers. Most of the information is specific to *Parastichopus californicus*, the giant red sea cucumber common to the West Coast of North America between Baja California and the eastern Gulf of Alaska.

Parastichopus californicus is classified as follows:

Phylum Echinodermata
- Class Holothuroidea
  - Order Aspidochirota
    - Family Stichopodidae

Mottet (1976) provided an excellent overview of occurrence, patterns of utilization, and biology of both the commercial sea cucumber in Japan (*Stichopus japonicus*) and *Parastichopus californicus* on the west coast of North America. Tube feet, water vascular system, radial symmetry and nervous systems are similar and comparable to other echinoderms. Its nervous system is limited largely to a circumoral neural ring.

Oral tentacles are described as simple, compared to that of other sea cucumber species, and are used for ingesting mud, sand, detritus. The species ingests and voids large amounts of indigestible debris. Tube feet have multiple uses, including anchoring to substrate, locomotion, respiration and sensory reception. Tube feet are limited to only pulling movements, which restricts movement on silt or mud substrates that offer little purchase. Tube feet for locomotion are limited in this species to the ventral side of the animal, along three ambulacra, or grooves. Papillae on the dorsal side are modified tube feet. These knobby bumps are a desirable marketing feature.

The body wall is filled with fluid similar to sea water. The percent of body weight composed of this fluid may approach 90% seasonally. Fluid content is higher during periods of low feeding activity, when the animal utilizes nutrients stored in the body wall.

The body wall is made up of several layers: cuticle, epidermis, and dermis. The dermal layer is heaviest and makes up most of the body wall. Calcareous spicules imbedded in the dermis provide stiffening, friction, and are sufficiently species-specific to use for taxonomic identification.

Attached to the inside of the body wall are lateral circular muscles which contract to lengthen the animal. Inside the circular muscles, and attached to them at a 90° angle, are five sets of longitudinal muscles.

Contraction of the longitudinals shorten the animal. Longitudinals are much better developed than the circular muscle bundles.

Respiratory trees are large branched organs attached to the cloaca that transport fresh, oxygenated water deep into the sea cucumber's body. Pumping is done by cloacal muscles. In sequence, the anus opens, the cloaca expands, the anus closes, the cloaca contracts, and the trees fill; as oxygen is extracted and depleted, the process is reversed and water is expelled. Trees are not essential for respiration because the animal also uses its body wall extensively for respiration. During low activity periods, respiration through the body wall is enough to maintain life.

Length and Weight

Unlike many animals which either grow at constant rates or asymptotically for most of their natural lives, adult and juvenile *P. californicus* undergo seasonal gains and losses in weight. These changes affect the internal organs to a greater extent than the body wall and associated musculature. Although there is a net increase in individual length and weight during its life span, analysis of growth has to consider seasonal changes in these parameters. Although Mottet (1976) did not specify conditions of measurement, length to width ratios were reported as about 5:1. She also reported a maximum length of up to 500 mm, assumed to be during relaxation or full extension.

For adults, Fankboner and Cameron (1985) reported that up to 25% of maximum summer weight was lost during the winter, mainly due to visceral atrophy. They asserted that visceral atrophy is a gradual process, rather than the autoevisceration reported by earlier researchers studying this behavior. The catabolic process begins in September, when the adults stop eating and become lethargic, feeding and moving less actively. Paradoxically, the animals appear to be more sensitive to disturbance at this time, commonly responding to handling by more readily auto-eviscerating than at other periods of the year.

The gonad, water circulatory system, respiratory trees, and digestive system are all reduced to remnant primordial tissue by late winter, typically January and February. Regeneration starts within a week of total resorption. The digestive system is the first to start redevelopment, followed by respiratory trees, circulatory system, and gonads. Body wall mass follows a cycle with lowest weight at the point in time when regeneration begins and highest weight at the onset of visceral degeneration in the autumn. Condition is recovered during the feeding period in spring and summer months. Fankboner and Cameron (1985) suggested the term "diapause" to describe this behavior.

They postulate that this behavior is regulated somehow by sunlight or by synchrony with autumn blooms and variations in food availability. They note that animals in aquaria without food cease feeding behavior and enter diapause up to 60 days before animals in the field.

Cameron and Fankboner (1989) reported that body size of juveniles also decreased between October and December. Juveniles undergo similar cycles of atrophy and regeneration, which are, except for the absence of the gonadal resorption, somewhat analogous to that of adults. Juvenile cycle timing is even more asynchronous than that of adults, with portions of the juvenile segment of the population in different stages at any given time during the fall.

Reproduction

Mottet (1976) reports a single gonad as usual in this species. Sexes are separate (Cameron and Fankboner 1986). Gonopores of both sexes are similar and located antero-dorsally. There is very little sexual dimorphism. Cameron and Fankboner (1986) reported sex ratios over a period of 19 months in British Columbia as not differing significantly from 1:1. They found gonadal indexes at their lowest annual levels in November and December. Proliferation of the reproductive system starts in January and February. Most animals are also actively feeding during this period. Maximum gonad size is in June, July and August, then begins decreasing in September and is smallest in November and December.

The species is a broadcast spawner, with the male triggering the spawning response. Fully mature females release up to several million eggs over the length of the protracted spawning period. Repeated spawning episodes may occur during the spawning period. Spawning behavior is described as an elevation of the anterior end off the substrate, with the gonopore held at maximum height above the substrate. Spawning is simultaneous among portions of the population but epidemic spawning, simultaneous spawning on a large scale, has never been observed or reported. Sperm are visible as a white cloud, but eggs are almost invisible due to their coloration. Egg dispersion is almost immediate under most field conditions. No spawning aggregations were ever seen by Cameron and Fankboner (1986), and observed distances between spawning individuals were reported as up to 10 meters apart.

Peak spawning occurs between June and August in both Washington State and British Columbia (Courtney 1927; McEuen 1988; Cameron and Fankboner 1986). Early spawning records include May in Washington State (Cameron and Fankboner 1986; McEuen 1988), April in British Columbia (Cameron and Fankboner 1986), and an extreme early spawning record of March 26 in British Columbia for one male only (Cameron and Fankboner 1986). In the laboratory, spawning has occurred as early as April (McEuen

1988). Gonadal size indices indicate that spawning potentially occurs through September in British Columbia (Cameron and Fankboner 1986).

Spawning appears to be associated with periods of bright sunshine and phytoplankton blooms (Cameron and Fankboner 1986; McEuen 1988). Spawning events may not be directly related to temperature, although the reproductive cycle is associated with spring and summer warming (Cameron and Fankboner 1986). There appear to be a higher percent of mature spawners in shallow water along shore than in water 16-80 meters deep (Courtney 1927). *In situ* salinities at spawning are about 27 to 28 parts per thousand (Cameron and Fankboner 1989).

Recently, Alaska Department of Fish and Game divers reported that individual sea cucumbers were observed in the spawning posture in early April in southern Southeast Alaska. There have also been unconfirmed reports from commercial divers that this behavior has been observed in more central districts in Southeast Alaska in early April. In conclusion, spawning seasons for *P. californicus* appear to be protracted and inter-annually variable, but spawning probably occurs in late spring and summer.

Age and Growth

Strathmann (1978), using animals held in the laboratory, reported 51 to 91 days from egg fertilization to larval settling. Thirty-seven days transpired between the auricularia and doliolaria, or first and last, larval stages. He postulated longer pelagic periods as likely at higher latitudes.

Cameron and Fankboner (1989) also remark on the great asynchrony of development, even of simultaneously fertilized ova. They report up to 127 days between egg fertilization and settlement of the pentactula. Pentactula have five buccal podia and a single posterioventral pedicle, readily attach to the substrate, and are considered either the last larval or first juvenile stage. Juveniles in the field (4-8 months post-settlement) are first apparent at about 0.3 to 1.0 cm contracted length. They are 0.5 to 1.9 cm contracted length at 7-11 months, closely approximating Strathmann's (1978) results. Cloacal pumping, associated with respiratory movements, is first observed at about 7 months.

Growth of juveniles is greatest in summer and spring and least in winter. Growth results by lengthening of the body anteriorly from the larval posterioventral foot. By the end of year 0+, animals have eight to 48 tube feet, 15 to 44 dorsal papilli (projections or protrusions on their backs) and 13 to 17 buccal tentacles (early feeding tentacles around the mouth).

A size index developed by Cameron and Fankboner (1989), as a means to measure growth and age, is equal to contracted length times contracted width times a scaling factor of 0.1. Mean index values are 1.01 in year 1, 4.45 in year 2, 8.97 in year 3, and 13.4 in year 4. The size index is correlated to stripped weight and can be expressed by the linear equation $y = 7.796x - 7.339$ ($r = 0.96$, $n = 61$), where y = predicted body weight in grams and x = size index for ages 1 to 4 years.

The color of sea cucumbers early in their first year is usually white, larger 0+ animals are pink dorsally, second year animals are red-maroon, similar to the red algae upon which juveniles are commonly found. Animals may recruit to the juvenile stage over a 5 month period. The long pelagic stage may be an adaptation for minimizing risk to a year class and mixing the gene pool. Local recruitment may be dependent to great extent on hydrographic conditions.

Cameron and Fankboner (1984) suggest that 0.5 cm to 2.0 cm animals are about 1 year old, based on their seasonal occurrence. Fankboner and Cameron (1988) consider sexually mature animals to be at least 56 months old, with a probable range in age of first maturity between four and eight years. They consider the maximum age of the species in British Columbia to be about 12 years (Fankboner, personal communication, 1990).

Food Habits

Brenchley (1981) characterized this species as an epifaunal deposit feeder that also transports sediments and redistributes them in fecal pellets bound in mucus. Cameron and Fankboner (1984) reported that the species has 20 feeding tentacles arranged radially around the mouth. Each tentacle has a stalk, with four primary branches radiating outward, bifurcating into secondary, tertiary, and quaternary branches. Each tentacle is connected to the water vascular system. Feeding consists of repeated extension, collapse, and withdrawal of the tentacles placed against the substratum. Tentacles are randomly inserted into the mouth and wiped clean in the pharyngeal cavity. Adherence of food and sediment to the tentacles is by secretion of adhesive substance at the surface of the most distal nodules of the feeding tentacles.

Juvenile feeding habits are similar to that of adults (Cameron and Fankboner 1989). Juveniles use their posterior terminal tube feet to attach to the substrate and sweep the surrounding area with their circumoral tentacles.

Spatial Distribution/Habitat

Substrate

The species is commonly found in rocky intertidal and subtidal areas (Courtney 1927; Cameron and Fankboner 1989). Juveniles prefer mats of filamentous red algae or parchment tubes of the sedentary polychaete *Phyllochaetopterus prolifica*, which also harbor red algae, as substrates. Age 0+ juveniles are also found in crevices on near-vertical rock walls, generally at depths of about 10 meters.

Current

Although the species can withstand currents up to about 2.5 knots (Da Silva et al. 1986, Cameron and Fankboner 1989), it avoids areas with strong wave action, preferring quieter bays and pilings.

Depth

The species has been reported from intertidal waters in British Columbia (Cameron and Fankboner 1989) to a depth of 249 meters off Kodiak Island (Lambert 1984, 1986). While they have been reported to depths of 150 meters in the San Juan Islands of Washington State (Shelford and Towler 1925), Fankboner and Cameron (1985) never found them deeper than 25 meters in their study areas in British Columbia. However, in the southern end of its range in California, it apparently prefers depths greater than 30 meters (Yingst 1982). It is evident that the species is distributed from the shoreline to considerably deeper depths over much of its range.

Migration/Locomotion

Mottet (1976) reported known crawling rates for some species of sea cucumbers of up to 100 meters in 24 hours. *P. californicus* is capable of sinusoidal swimming motions (Margolin 1976), generally used as an avoidance response when certain species of predatory sea stars are contacted.

However, in most circumstances, the species crawls randomly throughout its habitat without any directional preference or intraspecific influence (Da Silva et al. 1986). There were no indications of short-term (less than three months) tendencies to aggregate for feeding or spawning.

Passing references in the literature allude to reaction to probing by movement away from stimulus and contraction of longitudinals upon increased stimuli. More persistent handling occasionally causes evisceration of the animal's internal organs, which is thought to be a defensive mechanism.

Cameron and Fankboner (1989) found that small juveniles were readily eaten by sea stars until about 3 years post-settlement, when animals grew big enough to evade or frustrate sea stars. Adults held in aquaria with sea stars over periods of two to six months were occasionally attacked but not consumed. They found the escape response to be less developed for younger juveniles and more developed for progressively larger animals.

Interspecific Relationships

Parasites/Symbionts

Cameron and Fankboner (1989) reported finding low levels of the scale worm *Arctonoe pulchra* on this sea cucumber. Ten percent of juveniles at one collection site had the endoparasitic gastropod *Comenteroxenous parastichopoli* attached to the anterior region of the esophagus. Some juveniles and adults had an unidentified sporozoan in their digestive tract.

Prey

Bingham and Braithwaite (1986) found sea cucumber tissues in digestive tracts of three of 47 kelp greenling (*Hexagrammos decagrammus*). Cameron (unpublished) observed hermit crab attack and eat small age 1+ animals.

Intraspecific Relationships

Cameron and Fankboner (1989) considered population densities of 0.5 per square meter as high. Larvae tend to settle in areas where adults are present (Fankboner, personal communication, 1990). Surprisingly, juveniles are rarely found with adults, perhaps due to the adults' common coexistence with predatory sea stars which are known to attack juvenile sea cucumbers. Juveniles are usually in areas devoid of sea stars.

Ecological Significance

Brenchley (1981) described cucumbers as "bioturbators" that influence their environment by reworking and redistributing sediment in the process of feeding on the detritus constantly settling on the substrate. They influence the occurrence and abundance of other members of the nearshore ecosystem. Their ecological significance beyond this is currently unknown and a cause for speculation.

HISTORY OF THE SEA CUCUMBER FISHERY IN THE EASTERN PACIFIC OCEAN

Washington State

The Washington State sea cucumber fishery began in 1971 and stayed relatively small until after the collapse of the sea urchin fishery in 1980.

Before 1987, sea cucumbers were commercially harvested by divers without either seasonal or areal restrictions. In 1987 signs of overfishing prompted the Washington Department of Fisheries to divide state waters into four harvest districts (San Juan Islands, Strait of Juan de Fuca, Central Puget Sound, and South Puget Sound/Hood Canal) and restrict the season to May 1 through October 31. The seasonal restriction was imposed to limit fishing effort, and winter was chosen as the closed period because sea cucumber body weight apparently declines during this time.

Eighty-five special permits were issued in 1988 for cucumber diving, and 78 vessels actually participated. This effort level represented a three-fold increase from the 1987 season, when only 25 dive vessels sold cucumbers. Overall, Washington State divers sold 1.9 million pounds of sea cucumbers during the 1988 season, a record catch for the industry.

British Columbia

The British Columbia sea cucumber fishery began in the southern part of the province in 1980 (Jamieson 1986; Sloan and Harbo 1987). Commercial concentrations at the time were over 0.25 cucumbers per square meter. At this density, a diver can harvest up to 2,500 animals per day. In 1988, 79 vessels participated in the fishery. The total harvest was 1,931 tons, with an ex-vessel value about $984,000 Canadian. During the past two years there has been an increase in utilization of the cucumber skin as a dried product as well as the traditional frozen muscle strip products.

Arbitrary management quotas have been set for various portions of the British Columbia coast until more biological information can be gathered. Quotas were reduced by 400 tons in 1989 for the south coast due to concern that the stocks were being overexploited. The fisheries were short for the south coast in 1989. The inside waters, with a 300 ton quota, were closed January 19, and the west coast of Vancouver Island on February 15. The quotas for the north coast were split into three districts in 1989: the Prince Rupert District (170 tons, closed on March 3), the Queen Charlotte Islands (160 tons, closed April 24), and the Central Coast (170 tons, closed January 16). The 1990 season for most areas was even shorter, with all fisheries closing by mid-February.

Alaska

Ketchikan Regulatory Area

The Department of Fish and Game was requested in April, 1987, to consider the commercial harvest of sea cucumbers in the Ketchikan area. This request originated from local divers who were in contact with a seafood processor located in Washington State. Prior to issuing any harvest permits, the local staff decided it was necessary to investigate the biological aspects of the animal, review current management techniques in other areas, and determine if commercial quantities existed locally. Through discussion with divers in the industry, Vallenar Bay (12 km northeast of Ketchikan) was selected as a study area. Dive surveys were conducted by department staff in order to determine sea cucumber density levels in Vallenar Bay. The density information led to a population estimate between the depths of zero and 60 feet, the general working range of commercial divers. A harvest quota was set for the area at 5% of the estimated biomass. (The 5% harvest was used to reflect a conservative approach to the fishery, as the fishery was considered experimental.) Permits were then issued to local divers for the harvest of sea cucumbers in the Vallenar Bay area starting on May 1.

In October 1987, divers requested a new area to fish due to declining sea cucumber densities in Vallenar Bay. The second area that was opened for harvesting was Moria Sound. Harvesting in this area occurred from November 4 to December 12. The management differed somewhat from Vallenar Bay, as small areas within Moira Sound had individual quotas, derived from density estimates of sea cucumbers surveyed previously in Vallenar Bay, and the effort was moved as these quotas were filled. The industry and divers experienced problems with transporting the product back to Ketchikan due to winter storms and having to cross Clarence Strait. Therefore, the department was approached with a request for a new harvest area closer to town.

The fishery was moved to a third area, a portion of Carroll Inlet, between Island Point and Brunn Point, where fishing started on December 7, 1987. The fishery closed in January of 1988, because the local processor did not renew its intent to operate.

Between late August, 1988, and late April, 1989, permits were issued for the harvesting of sea cucumbers for different time periods in areas near Ketchikan, namely George Inlet, the Bold Island area, Carroll Inlet, Tongass Narrows, Clover Passage, Moser Bay, Thorne Arm, and near Mary Island. The management strategy was based on separate quotas for subareas within each of these areas.

By the end of April, 1989, department staff recognized the need to develop a long-term approach to the fishery and, in a meeting held in Ketchikan, a rotational management strategy was developed. The plan consisted of three year harvest rotations by statistical subdistrict, each with a specific harvest quota based on abundance estimates derived from the Vallenar Bay surveys. In addition, areas were reserved for subsistence harvest only, or as control areas, and one continuous harvest area was designated in the vicinity of Vallenar Bay. The grouping of subdistricts for a particular rotational period was determined by a balanced mix of accessible and remote areas. Each rotational period was estimated to have similar overall harvest production potentials.

The rotational groups consisted of statistical subdistricts. Quotas, calculated for each subdistrict, were based on estimates of 11,000 cucumbers per nautical mile (this was based on density information derived from the Vallenar Bay area and would later be changed to 2,615 cucumbers per nautical mile after additional density information was collected in the fall of 1989. A conservative harvest policy was implemented that was designed to harvest only 5% of the available cucumber population. The annual beginning date for each rotation was set as July 1.

For the 1989-1990 season, Rotational Group 1 was open for harvesting (Table 1). In addition, there was a continuous harvest area open on the west side of Gravina Island. The fishery was primarily a day boat fishery until mid-December, 1989, when larger vessels (up to 70') entered the fishery with several divers and tenders on board. This dramatically increased the harvest rates. Once the quota for a subdistrict was taken no further harvest permits were issued for that subdistrict, effectively closing it.

In October 1989, the department was approached by divers, particularly those operating out of Craig, concerning the commercial harvesting of sea cucumbers on the west coast of Prince of Wales Island, in Districts 3 and 4. Due to possible conflicts between commercial and subsistence uses, the majority of District 3 was closed to commercial fishing until the extent of subsistence use in the area could be identified. This left District 4 and the northern portion of District 3, namely Sea Otter Sound, for possible entry by commercial harvesters. Sea Otter Sound was opened in mid January, 1990, and no quota was set. The area was closed with the rest on May 5, 1990. Approximately 400,000 lbs of sea cucumbers were harvested from the southern third of Sea Otter Sound in less than four months.

Sitka Regulatory Area

The first permit for the harvesting of sea cucumbers in the Sitka area was issued on December 6, 1988. It was the only permit issued for the area that year. The permit was issued for a two week period, and a log book was required. The entire portion of District 13B north of Dorothy Narrows was open for harvesting.

In 1989 there were 60 permits issued. Effort in the fishery started off fairly low, and increased as the year progressed. Between January and April only four permits were issued. The permits were issued for two week periods, and once again the entire portion of District 13B north of Dorothy Narrows was open for the harvesting of sea cucumbers.

Beginning August 16, 1989, Sitka Sound was divided up into three rotational areas. A quota system for the three rotational areas was instituted based on test fishing done in the Ketchikan area. Originally the quotas were based on a density estimate obtained from the survey in Vallenar Bay in April of 1987 and revised following surveys there in September 1989.

Beginning August 16, 1989, the system was changed to a monthly permit system rather than a two week permit system. The northernmost rotational area was opened at this time, but the other two areas remained closed. The closed portion of District 13B was south of a line from a navigational light located approximately 1/2 mile north of Lisianski Point to Mountain Point and north of the latitude of Frosty Reef. All of the remaining portions of District 13 were opened at this time to exploratory fishing. Beginning December 1, 1989, the northernmost rotational area was closed to harvesting because of high harvest levels. Therefore, all of the rotational areas within Sitka Sound were closed. However, the remainder of the District was still open for harvesting.

On December 21, 1989, local subsistence users and a subcommittee appointed by the Sitka Fish and Game Advisory Committee met to establish an area in Sitka Sound which would be set aside as a personal use and study area that would be closed to commercial fishing. The group agreed that the personal use/study area would be all waters of Starrigavan Bay, Katlian Bay and the west shore of the Lisianski Peninsula east of a line from Harbor Point to Big Gavanski Island Light to Dog Point. This area designation went into effect on January 1, 1990 and the area was closed to commercial harvest. Beginning January 1, 1990, the central rotational area was opened for commercial harvesting. It remained open until May 5, 1990, when it was closed with the rest of Southeast Alaska.

There is only one sea cucumber processor located in Sitka at the present time. Alaskan Harvest, Inc. began operations the beginning of April, 1989. Prior to the opening of Alaskan Harvest, Inc. there was one other processor, Great Northern Seafoods, which opened in December of 1988 but ceased operations in April of 1989 at about the same time that Alaskan Harvest, Inc. came into being.

Petersburg Regulatory Area

Harvest of sea cucumbers in Petersburg has occurred sporadically over the past two years. Effort increased area early in 1990 as a result of closure of subdistricts in the adjacent Ketchikan Area.

In response to the increasing number of requests for exploratory permits, the Petersburg Management staff established a set of rotational areas similar to that of Ketchikan in order to direct effort during exploratory fishing surveys. Most of the allowable harvests in the southern portion of the Petersburg area were quickly taken and the areas closed. Less effort occurred in the open districts in the northern portion of the Petersburg area and the fishery was still open when the entire region was closed on 5 May.

Juneau Regulatory Area

The harvesting of sea cucumbers in the vicinity of Juneau has consisted of an exploratory harvest by one individual using one permit and one boat in September of 1989. In Tenakee Inlet, a floating processor supporting a group of divers conducted exploratory fisheries in April of 1990. Additional interest was developing in harvesting sea cucumbers from the southwestern shores of Admiralty Island when the fishery closed.

Tables 2-4 summarize the historical catch for the Southeast Alaska sea cucumber fishery and provide some perspective for the magnitude of the changes which occurred between 1987 and 1990.

History of Development of Assessment Methods

Field surveys were initiated by the Alaska Department of Fish and Game in April 1987. The first survey, conducted at Vallenar Bay, demonstrated the applicability of SCUBA transect methods for estimating abundance. As the bay was in demand as a commercial harvest site, the survey also served as a baseline estimate of virgin biomass. Subsequently, the expanding fishery dictated expanded surveys to account for possible areal differences on fishing grounds around Ketchikan and Sitka. Additional surveys were conducted September 6-11, 1989, in various bays and habitats around Ketchikan. Two of the original 1987 transects were resurveyed in 1989 for comparative purposes.

A number of assumptions were incorporated into the sample design. It was assumed that 60 feet was the maximum workable non-decompression limit for commercial diving; hence, the maximum depth for transects was limited to 60 feet, although it was known that sea cucumbers could be found at considerably greater depths.

Transects were established in 1987 by identifying a landmark, at or near, the tideline as a starting point, using a skiff with a fathometer to anchor a reference buoy at a point 60 feet in depth and approximately perpendicular to shore or the prevailing bottom contour, and by using a range finder to estimate the length of the transect. Once the transect was set, divers were slowly towed from shore to the reference buoy by skiff. At approximately seven to ten meter intervals (about 15 seconds of towing time), the skiff stopped and the diver conducted a meter-square count of sea cucumbers at that point. This process was repeated until the buoy, and the end of the transect at 60 foot depth, was reached. This transect method was originally developed for estimation of herring roe deposition.

The methodology employed for the 1989 surveys differed from that of 1987. A deliberate attempt was made to select a variety of habitats to better define the relationship between habitat and sea cucumber abundance. Rather than use a buoy for reference, divers took a compass bearing from shore and followed it out to the 60 foot depth. Also, instead of using meter square counts, counts were made of all sea cucumbers within a one meter strip transect. Another difference was that an area-swept method was used in 1989 rather than the quadrat system of 1987. The 1989 surveys also included a wider variety of habitat types and many of the transects were videotaped for future reference. The area-swept method is probably better suited to the aggregated nature of sea cucumbers and will be employed for future surveys.

The average number of sea cucumbers in the 1987 surveys was 0.69 animals per square meter. Based on this average density and its total calculated square meters, a population of 1,449,000 sea cucumbers was estimated for Vallenar Bay.

Using the area-swept method the average number of sea cucumbers in all the habitats and bays surveyed was estimated to be 0.24 animals per square meter. Two of the original 1987 transects in Vallenar Bay were resampled in 1989. In 1987, an average of 0.50 sea cucumbers per square meter was determined for transects 1 and 4. In 1989, the average had dropped to 0.35 per square meter. Although a population reduction was suggested, the limited number of transects does not statistically implicate the commercial fishery as the primary cause of the decline.

Before the 1989 surveys, the method of estimation of total virgin biomass for an area was to multiply the average density per square meter (0.69 animals obtained from Vallenar Bay) by the area in square meters between the depths of zero and 60 feet. Areal determinations were obtained with a planimeter.

Total virgin biomass was estimated from the 1989 survey data by multiplying the miles of shoreline in an area by the average transect width to obtain the estimated area between 0 and 60 feet, and then multiplying this product by the average density per square meter (0.24 animals) obtained from all 1989 survey data. This method was used to obtain estimated biomass figures for statistical subdistricts or fishing areas.

A 5% harvest rate for each subdistrict, once every three years, was established for the Ketchikan area. This resulted in a 1.67% annual harvest rate with a single opening of each area once every three years. This low harvest rate was considered conservative and appropriate given the unknowns associated with the abundance estimates and life history of the sea cucumber.

HARVEST RATE DETERMINATIONS FOR SEA CUCUMBERS

Overview

Harvest rates for *Parastichopus californicus* are set to achieve the biological conservation objective by preventing recruitment overfishing. Conservative catch quotas are set to meet this objective for the following reasons. First, sea cucumbers have life history parameters, including irregular recruitment and low maximum yield per recruit, which in theory, make them vulnerable to high harvest rates. Imposition of high catch quotas could lead to fishery collapse after several years of poor recruitment. Second, because larvae appear to settle only in the vicinity of adult sea cucumbers (Fankboner, personal communication 1990), complete removal of adults could prevent recruitment of young animals to the fished area. Third, because adults seem to migrate slowly, repopulation of overexploited areas may take many years. Fourth, due to lack of data, only surplus production models can be used to determine yield; parameters for this model type are difficult to estimate, and fisheries to which these models are applied without caution tend to run great risk of collapse. Last, large uncertainties currently exist in estimates of population size.

Implications of Life History Parameters of P. californicus on Fishery Yield

Adams (1980) considered the theoretical consequences of the following life history parameters on fisheries management strategies: age at first maturity, maximum age, growth rate, mean asymptotic weight, and natural mortality rates. These parameters and their consequences for management are summarized below for *Parastichopus californicus.*

First maturity of *P. californicus* occurs at ages 4-8 in British Columbia (Cameron and Fankboner 1988). Maximum age is at least 12 years based on size frequency observations (Fankboner, personal communication, 1990). Because animals of the same species tend to grow slower and live longer at higher latitudes, we assume the maximum age of *P. californicus* to be 14 years in Southeast Alaska. Size at sexual maturity and commercial harvest is approximately 1.1 lbs (Sloan 1986), and mean asymptotic weight is probably similar. Maximum size in length is approximately 1.5 feet (Mottet 1976). Rough estimates of natural mortality can be predicted from maximum age by a predictive regression developed by Hoenig (1983). Given a maximum age of 14 years, Hoenig's (1983) equation predicts an instantaneous natural mortality rate (M) of 0.32, which corresponds to an annual mortality rate (i.e., percentage of sea cucumbers that die annually due to natural causes) of 27%. Results from other species with a maximum age of 14 years cited in Hoenig (1983) suggest that the true value of M may range from 0.16 (15% annual mortality) to 0.75 (53% annual mortality).

Relative to other species classified by Adams (1980), sea cucumbers demonstrate a low age at first maturity, low maximum age, low mean asymptotic weight, and high natural mortality. Adams (1980) found that species with these traits tend to have a low maximum yield per recruit and are particularly vulnerable to overfishing.

Three other life history traits suggest that sea cucumbers are vulnerable to recruitment overfishing. First, in experiments conducted in British Columbia, Fankboner (personal communication 1990) found that larvae appear to only settle in the vicinity of adult sea cucumbers. No young sea cucumbers were recruited to areas in which all adults were removed, yet young settled into adjacent areas where adults were still present. Second, Rutherford (1973) found that sea cucumbers migrate into new areas very slowly; i.e., depletion of cucumber stocks by overfishing would not result in rapid replacement by adults from nearby areas. Further, young settled into the over-exploited areas only after several years when a few adults had migrated back into them. Fankboner (personal communication 1990) hypothesized that adults may emit a pheromone that triggers larval settling. If true, severe overfishing of sea cucumber populations would have major, long-term adverse impacts on local stocks. Third, recruitment of sea cucumbers tends to be irregular both spatially and temporally (Cameron and Fankboner 1989; Ebert 1983). It is common to observe several years with little or no recruitment. This is disconcerting because of the finding of Swartzman et al. (1983) that stock depletion may occur after several years of poor recruitment even after catch quotas have been imposed.

Methods for Determining Annual Yield

Due to the lack of understanding of sea cucumber population dynamics, only simple models of population growth, known as surplus production models, are applicable to setting harvest rates. These models must be used with caution, because they have numerous assumptions which are not yet verifiable for sea cucumbers. Therefore, these models are applied conservatively.

Two types of surplus production models will be used. The first is a model designed for application to new and generally unexploited fisheries, and this will be the model used to set harvest quotas in at least the first several years of commercial openings in Southeast Alaska. The second model type is designed for use with exploited fisheries for which recent catch data are available, and this will be applied when local populations of sea cucumbers have been exploited to a level beyond which the first type of model no longer applies. Both model types are described by Garcia et al. (1989).

Surplus production models are based on the concept of maximum sustainable yield (MSY), which is the theoretical maximum yield that can be extracted from a population at optimum stock levels on an annual sustained basis. Partly because marine populations do not exist in equilibrium conditions due to annual variations in recruitment, growth, and mortality, management toward MSY is no longer recommended (Larkin 1977). However, surplus production models which estimate MSY can be corrected for improper assumptions and uncertainties, and this is the approach adapted here.

Gulland (1971) proposed that $MSY = 0.5\ M\ B_0$, where M is instantaneous natural mortality and B_0 is virgin biomass. This equation assumes that the population grows according to the logistic population model, which does not account for spatial or temporal variability in the environment, nor for age or size structure in the population. This equation also assumes that the proportion of the population that can be harvested (termed F_{MSY}) is equivalent to the proportion that would succumb naturally (M) in the absence of fishing. The several assumptions (many of which are embedded in the assumption of logistic growth) have led to numerous criticisms of the model (e.g., Francis 1974; Deriso 1982). As a result, a scaling factor of 0.4, rather than 0.5, is now more commonly used to account for F_{MSY} being less than M (Caddy 1986; Garcia et al. 1989), so that MSY = 0.4 M B_0. This simply means that some of the natural mortality includes animals that would not normally be harvested, such as undersized individuals. Further, Garcia et al. (1989) recommended a target maximum annual yield between 50-67% of MSY for unexploited or relatively unexploited stocks to account for environmental variability and additional uncertainties which are not considered by the logistic-based model.

Instantaneous natural mortality (M) for *P. californicus* is estimated as 0.32 using the regression equation of Hoenig (1983) where M is a function of maximum age. Based on the graph presented by Hoenig for a variety of species, the potential range in M is 0.16 to 0.75.

In summary, the preliminary estimate of the maximum yield for an unexploited population is calculated as a product:

$$\text{Annual Yield} = GF\ (0.4\ M\ P_0)$$

where

GF =	0.5	conservative correction factor due to Garcia et al. (1989) to allow for errors in assumptions upon which the surplus production model is based;
M =	0.32	estimated instantaneous mortality rate for sea cucumbers using method of Hoenig (1983); and
P_0 =		virgin population size, which is substituted for biomass.

The product of these factors is 0.064 P_0. In other words, maximum allowable annual yield is estimated to be 6.4% of the virgin population size.

Due to potential errors in the estimate of population size, the lower confidence bound for the mean population is used as an estimate of P_0. This lower bound is based on a 90% one-sided confidence interval. The lower bound is unlikely to be much greater than 80% of the mean due to natural variability in the spatial distribution of sea cucumbers as determined from preliminary surveys. Therefore, the maximum annual yield for sea cucumbers in Southeast Alaska is not likely to be allowed to exceed 5% of the mean estimate of unexploited population size.

The annual yield for *Parastichopus californicus* in Southeast Alaska is therefore determined with several conservative safeguards. These safeguards include using the lower value proposed by Garcia et al. (1989) to allow for error in model assumptions, and using the lower bound on the mean estimate of population size to allow for sampling error. These safeguards are needed because of: (1) risks of overfishing due to larval settling requirements; (3) risks of overfishing due to slow migration of adults; (4) risks of overfishing due to application of crude sustained yield models; and (5) lack of comprehensive assessment surveys of virgin populations in fishing areas.

There is no safeguard for error in estimating M. In contrast, there is no upward correction to the annual quota to allow for restocking by sea cucumbers which migrate up from depths beyond the commercial dive limits. Both factors are difficult to quantify based on current information. For this reason, the conservative approach embodied in the multiplicative yield equation will be used as a first approximation.

It is unlikely that improved estimates of M will be obtained in the near future, although better estimates of maximum age, from which M may be estimated (Hoenig 1983), may be obtained. Estimates of the contribution of sea cucumbers from deep waters may be made following studies of depth distribution and migration.

More Sophisticated Yield Determinations

Application of more sophisticated models of annual yield is desirable to improve estimates of sustainable yield without sacrificing conservation goals. More sophisticated models, including stochastic simulations (Sissenwine et al. 1988), require information on stock recruitment relationships and the sources of variability in recruitment.

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Table 1. Subdistricts open within the first rotation for the Ketchikan Commercial Fisheries Management Area, 1989-1990.

	Subdistricts	
Near town		101-45
	101-46	
	101-48	
District 1		101-23
	101-41	
	101-73	
	101-75	
	101-80	
District 2		102-10
	102-50	

Table 2. Landings of sea cucumbers in S.E. Alaska from January 1987 through April 1990, by district, in pounds.

District	Year 1987	1988	1989	1990
1	58,772	50,018	530,565	232,384
2	14,795		122,702	130,251
3				406,086
5			600	121,917
6				56,249
7				15,067
8				
9				95,232
10				2,400
11			45	
12				65,456
13			669,071	630,417
14				
15				
16				
Total	73,567	50,018	1,322,983	1,755,459

Table 3. Permit participation and harvest characteristics of the sea cumber fishery in S.E. Alaska from January 1987 through April 1990.

Season	Pounds	Number of Permits	Number of Landings	Average Pounds per Landing
1987	73,567	13	155	475
1988	50,018	5	75	667
1989	1,322,983	97	1,382	957
1990	1,755,459	182	1,731	1,014

Table 4. Monthly landings of sea cucumbers from Southeast Alaska from January 1987 through April 1990, in pounds.

Month	Year			
	1987	1988	1989	1990
January	2,171	444	31,715	284,984
February	0	1,853	58,318	361,041
March	0	0	27,945	614,279
April	0	0	34,906	457,610
May	3,989	0	45,114	37,545
June	0	0	78,454	
July	9,311	0	87,881	
August	8,437	6,759	193,795	
September	10,135	16,454	200,901	
October	5,995	1,017	218,658	
November	14,342	844	146,655	
December	19,187	22,647	198,641	
Total	73,567	50,018	1,322,983	1,755,459